

Wind-Induced Vibrations of Tall Buildings: The Role of Full-Scale Observations in Better Quantifying Habitability

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TABLE OF NOMENCLATURE

$\phi_i(z)$	Overall mode shape
$\phi_{i,A}(z)$	Axial mode shape component
$\phi_{i,V}(z)$	Frame racking mode shape component
$\phi_{i,PZ}(z)$	Panel zone mode shape component
$\tilde{\phi}(z)_i$	Approximate mode shape
z	Elevation
h	Total building height
α	Mode shape power
ξ	Critical damping ratio
f	Frequency

Abstract

The design of tall buildings, in many cases, is governed by habitability considerations whose satisfaction depends significantly upon two key aspects: first are the criteria used to establish the target limit state. These criteria are based on occupant comfort and can have a considerable effect on the efficiency and economy of modern tall building design, though there remains uncertainty surrounding the appropriate criteria, including the physical measures and waveforms best quantifying motion stimulus. Further, the ability of any design to meet these target criteria depends largely on the equivalent viscous damping levels assigned to the building. The basis for this assignment is rather qualitative and raises considerable uncertainty in the resulting acceleration response predictions. These and other lingering challenges prompted a long-term full-scale monitoring effort in Chicago by the authors and their colleagues, extending now internationally. This paper addresses several issues related to the perception issue in tall buildings: determination of realistic occupant comfort criteria, assessment of the faithfulness of predicted acceleration responses by current approaches, development of a more intuitive predictive model for damping, and the ability to calibrate this model using full-scale data, particularly for buildings featuring coupled response. This paper therefore canvasses these issues and value of full-scale observations in resolving them.

Introduction

As building systems become taller, more lightweight, and efficient, they become increasingly sensitive to the effects of wind. As a result, habitability limit states often govern the design of tall structures, as wind-induced accelerations increase and become more perceptible to occupants. Human perception of motion is dependent upon many factors, some of which are more difficult to quantify than others. While researchers have studied the

effects of frequency, amplitude, duration of motion, and waveform (peak factors) on human comfort using motion simulators, there are still other factors beyond these that contribute to motion perception and are difficult to accurately capture within motion simulators. In many cases, motion is not actually perceived until awareness is triggered by visible signs of motion, sounds generated by the motion, and even by word of mouth. In addition, the extent to which each contributing factor causes perception and/or discomfort varies from person to person, and the means to best quantify these accelerations (peak vs. RMS) is still contested [8]. The subsequent section will discuss some of these environmental factors that strongly influence the onset of perception based on full-scale observations.

Clearly the limit states associated with occupant comfort have their own uncertainties, and this is unfortunately compounded by uncertainties surrounding the prediction of dynamic response in the design stage. This paper will discuss two items in this regard: first is the fact that energetic transient events cannot be neglected in the assessment of structures for habitability. The second is the fact that regardless of whether transient or stationary response is being evaluated in design, neither can be done without an accurate estimate of damping. Damping plays a vital role in reducing acceleration responses. However, unlike mass and stiffness, the determination of damping is riddled with ambiguity. This problem arises from the many sources contributing to a building's inherent structural damping, which cannot be directly quantified and are generally dependent upon amplitude. In lieu of a theoretical means to determine damping in the design stage, empirical efforts have been undertaken by a number of researchers using databases of full-scale measurements [3,7,10]. Initially the parameterization of damping databases was performed with respect to height or period, after categorizing the data by primary construction material (steel or concrete). Although material and height are certainly important considerations in damping estimation, the significant amount of scatter observed in these parameterizations suggests that other variables should be explored. The authors have previously proposed a more intuitive model for damping estimation based on the dominant deformation mechanism of a structure, taking the structural system into consideration as well as building height and material [1]. Preliminary findings confirmed that shear-based deformations dissipate more energy than axial shortening associated with global cantilever behavior, and the relative contribution of these two components was shown to be a viable parameter for damping data regression. This paper will discuss this more intuitive model along with some of the fundamental challenges associated with the estimation of damping from full-scale data, particularly in the presence of modal coupling.

Quantifying Human Perception Criteria

The establishment of reliable occupant comfort criteria is an important goal toward the achievement of economic and efficient tall building design. Ideally, the permissible acceleration levels would be quantified through interviewing processes in realistic building environments instrumented so that the exact response of the building is known. Since it is impractical to extensively study the effects of building motion on human comfort in-situ, largely due to a lack of accessibility, studies have instead been historically performed in motion simulators. While these efforts have been underway for decades, many simulator studies utilize only sinusoidal motions. However, recent efforts have attempted to create more faithful testing environments, capable of simulating various waveforms on multiple axes to explore the influence of frequency, amplitude, duration, and peak factor [2]. The findings from these studies have particularly underscored the influence of waveform in human perception, exploring various peak factors on the simulated motions to achieve sinusoidal, narrowband and even transient events associated with gust fronts or thunderstorms. When considering actual building motion, these findings indicate that transient events may cause greater perception issues due to their sudden onset and high amplitude, but perhaps are not severely disruptive or negatively influencing comfort due to their short duration.

Although the motion simulator experience provides valuable information on the factors most influencing occupant comfort and perception, they may not capture the environmental factors that may cue motion at lower acceleration levels in actual buildings. Visual and audio cues in particular play a significant role in the perception of motion, but are difficult to reproduce in controlled simulator studies. In fact, an informal on-line survey (www.nd.edu/~tallbldg/survey.html) was developed by the authors and their colleagues to collect qualitative data on the perception issue in tall buildings. Initial findings presented in Kijewski-Correa et al. [5] chronicled multiple responses to a particular wind event where 70% of the respondents were looking out the window at the time they first perceived the motion. Interestingly, while 20% were first alerted by these visual cues, 80% did acknowledge the role of others in triggering their own perception. This factor is often not captured in controlled motion simulators, and since it is only achieved in group environments, perhaps becomes office buildings. 47% of solitary respondents (residential) indicate that they first perceived motion through audio cues such as squeaking, cracking and whistling, while 42% indicate that they felt the motion first. The remaining respondents indicated visual cues

as their first perception mechanism, with 6% citing “External motion cue: looking out the window” and another 6% citing “Internal motion cue: object swaying, liquid sloshing, etc”. It is interesting to note that visual cues were not a common perception trigger for the respondents, even though 57% of respondents were looking out a window while experiencing the motion.

Dynamic Response to Transient Events

Clearly waveform has some influence on perception; however, this presently is not accounted for in design-stage acceleration response prediction. For decades, wind tunnel testing has served as an important design tool for quantifying wind loads and ensuing acceleration responses; however, it is interesting to note that in some countries, particularly the United States, the most severe wind events, outside of hurricanes, are actually the result of gust front and thunderstorm activities not captured in the traditional boundary layer wind tunnel testing. Within the context of the Chicago Full-Scale Monitoring Program, transient wind events have been recorded and independent anecdotal evidence published in local papers confirms that occupant comfort or at minimum perception can be adversely affected in these transient events. Though not as common, similar transient events have been observed for another building in the program: a 264 m tall building located in Seoul, South Korea. This building has been instrumented with three orthogonal pairs of accelerometers attached to girders on the 64th floor, whose locations are shown in Figure 1. Pirnia et al. [9] investigated the dynamic properties of the building with a focus on amplitude dependence and closely spaced modes. These factors complicate system identification and extraction of dynamic properties in each direction.

Recent data from this building has shown significant responses to thunderstorm events, whose transient nature provides an impulsive-type stimulus to the building, exciting multiple modes with its broadband energy. Figure 1 shows the responses of the building to one such event that occurred on April 25th, 2008, through inset acceleration time histories and power spectral densities (PSD). Note that several of the higher modes are evident in the response, affirming the impulsive nature of this transient event, clearly visible at $t \approx 40$ minutes, particularly for the y-response. In this event, the wind before the transient was approaching from the East, moving parallel to the x-axis of the building. During the event, the wind changed direction rapidly, approaching parallel to the y-axis of the structure with markedly higher speeds. This may explain the greater impulse like responses at $t \approx 40$ minutes in this direction, particularly at Location 2 on the leeward edge. The full-scale observation of these types of events then raises important questions surrounding occupant comfort and its quantification: considering that the sudden onset of these events does cause perception complaints, should they be considered as design limit states for habitability and if so, how should they be predicted in design as deviants from the traditional wind tunnel testing protocols?

New Models for Damping

While both laboratory and full-scale perception studies continue in attempts to determine the most appropriate accelerations for habitability design, including the role of waveform, work needs to continue in hopes of predicting more faithful acceleration responses in the design stage so habitability requirements can be met in the formative stages of a project, without the need for costly retrofits later. Regardless of whether stationary events will remain the sole basis for design, any dynamic response analysis depends significantly on the specified damping ratio. Recognizing this, the authors [1] have worked toward improved damping models noting the influence of a structural system’s primary deformation mechanism on energy dissipation. It was found that buildings with a high contribution of frame racking, characterized by shear deformations in beams, columns and panel zones, had greater damping levels than buildings dominated by cantilever action, where the majority of deflections come from the axial lengthening and shortening of columns. These findings suggest that structural systems associated with taller, more slender buildings (tending to have dominant axial deformations) have less damping and therefore are more susceptible to occupant comfort issues. Since in-situ damping values are often less than those assumed in design, as affirmed by the full-scale case study on 9 tall buildings [7], designers are often confronted with buildings that meet perception criteria on paper, but in practice do not. It is hoped that the ability to better estimate damping levels in the design stage, based on the relative participation of shear vs. axial deformations, will allow designers to more accurately predict accelerations to enable pro-active redesign as needed.

This intuitive damping model was developed by analyzing the in-situ damping levels of numerous buildings worldwide, assuming the structural mode shapes consist of three components:

$$\phi_i(z) = \phi_{i,A}(z) + \phi_{i,V}(z) + \phi_{i,PZ}(z) \quad (1)$$

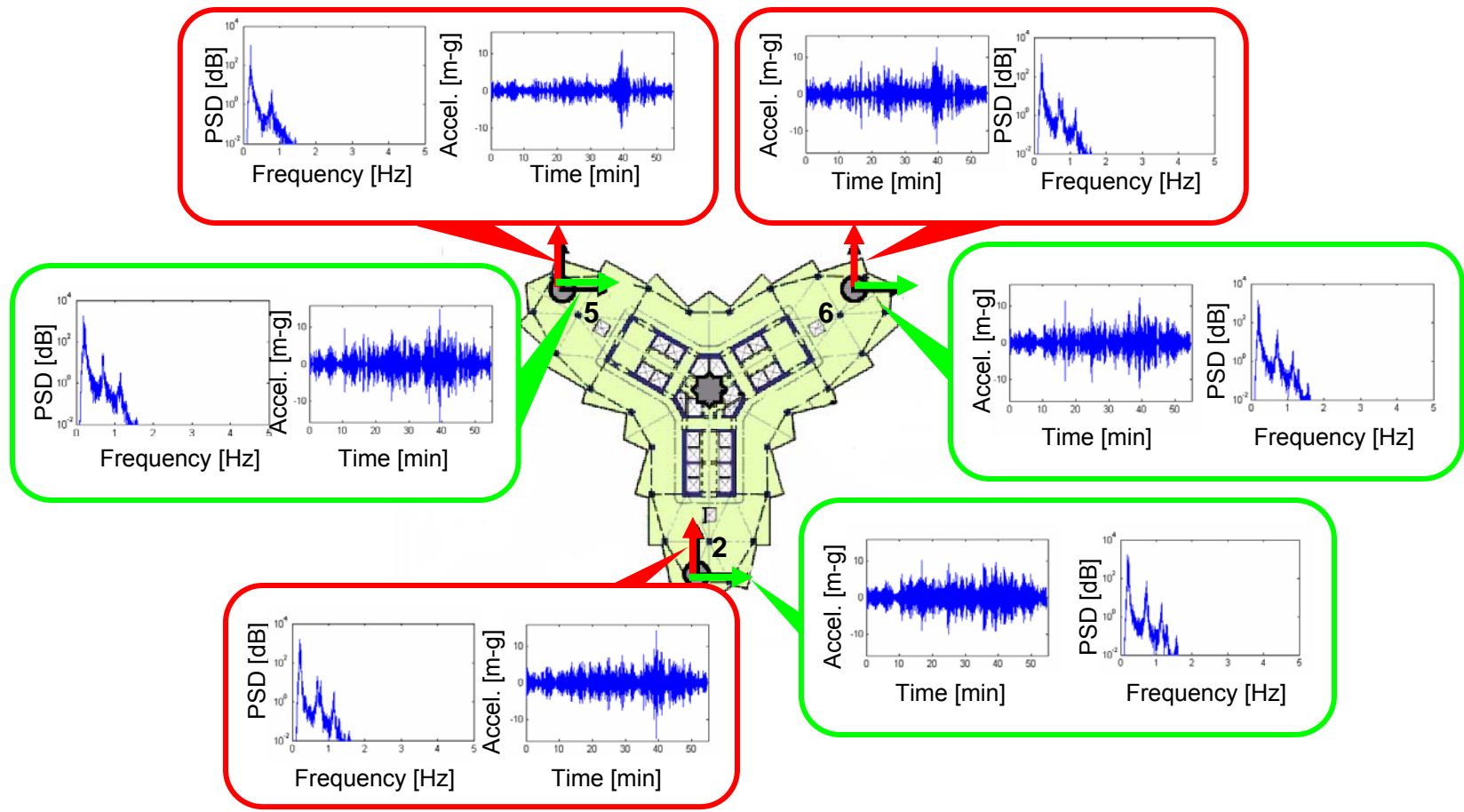


FIGURE 1- 64TH FLOOR PLAN SHOWING INSTRUMENT LOCATIONS AND DECOUPLED RESPONSE MEASUREMENTS AT EACH LOCATION, WITH INSET TIME HISTORY AND POWER SPECTRAL DENSITIES

Soliciting the help of the designers of the buildings, the authors have initiated campaign to determine the various components in (1) for all buildings for which in-situ damping levels are available. In cases where finite element models are not available or cannot be readily constructed from the public record, a basic fit to the overall mode shape by a power-law expression is used to provide qualitative estimates of the degree of cantilever action present [1]. In this case, the i^{th} mode shape is described by

$$\tilde{\phi}(z)_i = (z/h)^\alpha \quad (2)$$

and least squares minimization can be used to identify a best-fit power (α). For $\alpha \sim 1$, there is a general lack of cantilever action and as $\alpha \rightarrow 2$, there is an increasing presence of cantilever action. Often, $\alpha = 1$ is termed a “shear building” and $\alpha = 2$ is termed a “cantilever building,” as these signify benchmarks where around 75-80% of the deformations are contributed by the namesake. As such, the authors have adopted the following characterization of buildings based on the mode shape power [1]:

$$\begin{aligned} \text{Type V (Shear): } & \alpha \leq 1.25 \\ \text{Type A-V (Interactive): } & 1.25 < \alpha < 1.5 \\ \text{Type A (Cantilever): } & \alpha \geq 1.5 \end{aligned} \quad (3 \text{ a,b,c})$$

The effectiveness of this approximate characterization was verified in [1] using the FEM mode shapes of moment resisting frames with different aspect ratios. The approximation was then applied to actual building systems, including four structures from the Chicago Full-Scale Monitoring Program, with results affirming the general hypothesis previously stated [1]. At present, the authors are expanding the database of structures used in this new parameterization, again seeking the help of designers to better quantify the relative contributions of these deformation mechanisms.

The development of these predictive models is entirely reliant on the accuracy with which damping levels are specified. It can be rightfully argued that the scatter observed in full-scale damping databases is as much a function of the lack of appropriate parameterization as it is errors in the estimation of damping itself. Its estimation in lightly damped systems, in the presence of coupled modes and amplitude dependence is particularly challenging and requires sophisticated analysis techniques. To demonstrate this point, system identification was performed for stationary events occurring before and after the transient event previously documented in Figure 1. Despite the use of bandpass filtering and algebraic manipulation of sensor outputs assuming rigid body motion in plane, the individual responses on the building’s primary axes cannot always be isolated, depending on the response level and the degree of amplitude dependence that facilitates beating of modes [6]. In particular, the aforementioned Korean Tower had been previously analyzed in [9] using traditional filtering and decoupling approaches to isolate the contributions in both lateral directions and torsion. However, revisiting this same building for other wind events often results in residual coupling, despite these efforts. An example of this is shown in Figure 2, where random decrement signatures (RDS) extracted using the same methodology as Pirnia et al. [9] demonstrate clear beat phenomena between the lateral and torsional responses. As traditional filtering cannot be used to isolate these components, the wavelet transform paradigm introduced by Kijewski and Kareem [4] was instead consulted to visualize the intermittent presence of torsional response and effectively separate these two modes. Therefore, each random decrement signature was processed using time-frequency transforms with appropriate corrections for end effects [4]. Stationary wind events from west and southwesterly directions were considered. The westerly event generated the strongest responses for the x-direction, while the more southwesterly wind event generated the strongest responses for the y-direction. The mean frequency and damping estimates obtained by the random decrement technique with local averaging [9] are spatially depicted in Figure 2, with an example of the random decrement signatures. Visually the beating between sway and torsion is very evident, particularly in the x-direction (in fact, note that one of the y-responses shows no evidence of coupling) and becomes more pronounced at the leeward extremes of the structure due to the “fishtailing” similarly observed in a skyscraper in Boston [6]. The extent of coupling is very much dependent on the wind direction and amplitude, being largely facilitated by the amplitude-dependence previously noted by Pirnia et al [6]. Excellent repeatability is noted for the lateral frequencies at all three locations in Figure 2. The torsional frequency also shows good agreement, though generally taking on slightly larger values in the x-axis responses, perhaps due to differing amplitudes in the event analyzed for that direction. Interestingly, Pirnia et al. [9] provided expressions for amplitude dependent frequency in this building. Evaluating them for the amplitude levels herein: $f_x = -0.0027(0.2)+0.1992 = 0.198 \text{ Hz}$ and $f_y = -0.0023*0.2 + 0.2076 = 0.207 \text{ Hz}$. Thus in the presence of considerable coupling, the frequencies of vibration in individual modes appear to be somewhat softened.

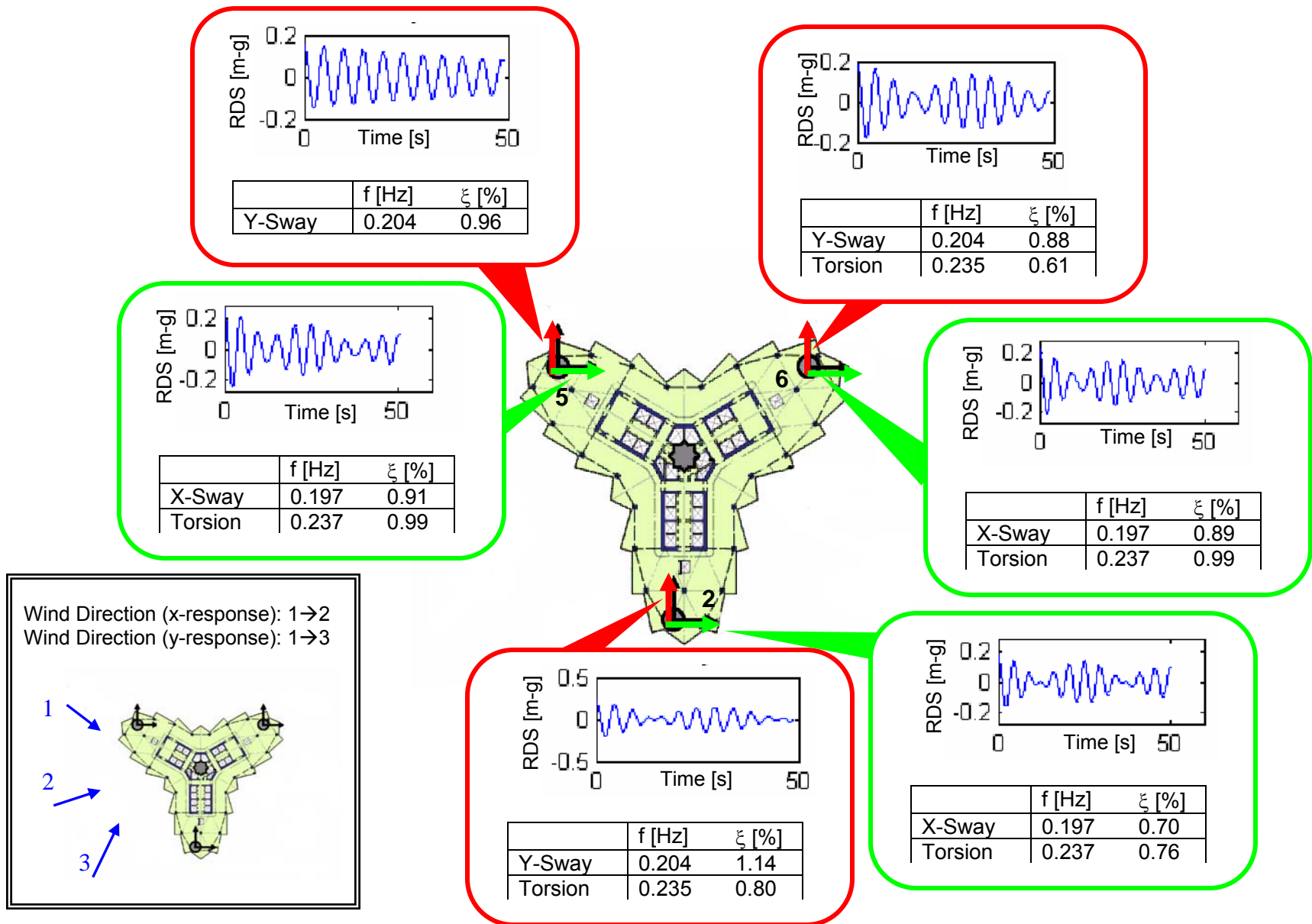


FIGURE 2- RESULTS OF SYSTEM IDENTIFICATION, DISPLAYED AT INSTRUMENT LOCATIONS (WIND DIRECTION SHOWN AS INSET)

Damping on the other hand shows an expected variability. Mode 1 (X-sway) shows an average damping of 0.83% critical (CoV 14%), while Mode 2 (Y-sway) shows an average damping of 0.99% critical (CoV 13%). Torsion was separately observed in two different events. In the first event, damping was an average of 0.7% critical (CoV 19%). In the second event, torsional damping was an average of 0.91% critical (CoV 15%). These events correspond to what would be in the lower-amplitude regime of Pirnia et al.'s [6] amplitude-dependent study. That study interestingly found damping values in this low amplitude regime to be highly variable and inflated. For example, damping values easily exceeded 1.5% in this regime for X-sway and then stabilized to a value of around 0.8% critical [6]. This prior study did not make use of any wavelet-based decoupling strategy to accommodate the coupled modes, and it is hypothesized, particularly at the lower amplitudes, that both modes were equally present in the response, leading to inflated damping values that are actually the aggregate of two closely spaced modes. As response increased, a particular mode may begin to dominate, such as lateral sway, allowing it to be readily isolated in the analysis. Thus it can be viewed that the 0.8% critical damping value is [6] probably is more representative of the inherent damping in the X-sway mode. This would then be consistent with what is observed in Figure 2: the wavelet analysis was successful in isolating the X-sway and extracting its damping value of approximately 0.83% critical. Applying similar metrics to the Y-sway response, Pirnia et al. [6] found that damping values stabilize at much lower amplitudes. Thus inflated values of damping (0.7% critical) rapidly stabilized with increasing amplitude to a value of 0.6% [6]. Considering that the effect of coupling was observed to be less prevalent in the Y-direction, these observations make intuitive sense: the inflated, coupled behavior would occupy a more limited amplitude range and the Y-sway response would rapidly dominate and be easily extracted, even without time-frequency aids. Note the low amplitude damping level in Figure 2 was 0.99%, in reasonable agreement with [6]. It should also be noted that Pirnia et al. [6] were unable to effectively isolate the torsional response, due to its minor and intermittent contributions, a capability now enabled by the wavelet analysis herein.

The effect of beating in building responses raises an interesting question regarding how damping should be specified. Generally, damping is assigned separately for each mode, however, in coupled buildings the internal tuning between modes can itself be an energy dissipative behavior, as clearly seen is the case in the decrement signatures in Figure 2. Therefore, should the modes be viewed in isolation, as the wavelet analysis permits, or should their aggregate effect be considered as the true measure of energy dissipative capability? Similar questions were raised in [6] and with respect to the issue of amplitude dependence in [9]. In fact, amplitude dependence, coupling and exchange of energy between modes generally go hand in hand. Damping estimates that do not consider time or amplitude dependent characteristics will not account for the role of intermittent coupling and beat phenomena or the exaggeration of spectral bandwidth that results when frequency content varies with amplitude. Instead they will provide an inflated damping value that may or may not be representative of the energy dissipation within the system or even more importantly the inherent damping associated with an individual mode. Furthermore, in the case of coupling, motions can even be amplified, as shown in [6], which in essence constitutes a negative damping contribution. Thus the one parameter that remains an enigma is often difficult to quantify even when full-scale data is available.

Conclusions

This paper has discussed the uncertainties surrounding human comfort criteria and efforts being made to better establish realistic design guidelines for accelerations, including the use of web-based occupant surveys, and the need to insure that design predictions of acceleration response are accurate reflections of in-situ behavior. In particular, this requires the need for more intuitive and accurate damping models, as well as an ability to assess the effects of transient events and their role in perception. This study additionally addressed the challenges that are faced when extracting damping values that become the bases for response predictions, particularly in the presence of coupling. Clearly human perception will continue to drive the design of tall buildings for many years to come, requiring refocused efforts at understanding the in-situ dynamic interactions between human and structure and more effective means to mitigate any adverse effects in the design stage to avoid costly retrofits and public scrutiny. As this study has demonstrated, full-scale observations have played and will continue to play a vital role in this regard.

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References

1. Bentz, A., and Kijewski-Correa, T., "Predictive Models for Damping in Buildings: The Role of Structural System Characteristics" Proceedings of the 8th Annual Structures Congress, 18th Analysis and Computation Specialty Conference, Vancouver, Canada, CD-ROM, 2008
2. Burton, M. D., Hitchcock, P. A., Kwok, K. C. S., and Roberts, R.D., "Acceptability Curves from Motion Simulator Investigations and Previous Experience with Building Motion," Tenth Americas Conference on Wind Engineering, p. 286, 2005
3. Jeary, A. P., "Damping in Tall Buildings- A Mechanism and Predictor," *Earthquake Engineering and Structural Dynamics*, 14, p.733-750, 1986
4. Kijewski, T. and Kareem, A., "Wavelet Transforms for System Identification in Civil Engineering", *Computer-Aided Civil and Infrastructure Engineering*, Vol. 18, No.5, p.339-355, 2003
5. Kijewski-Correa, T., Pirnia, J.D., Bashor, R., Kareem, A., Kilpatrick, J., Young, B., Galsworthy, J., Isyumov, N., Morrish, D. and Baker, W. "Full-Scale Performance Evaluation of Tall Buildings Under Winds," Proceedings of 12th International Conference on Wind Engineering, July 2-6, Cairns, Australia, Vol. 1, p.351-358, 2007
6. Kijewski-Correa, T. and Pirnia, J.D., "Dynamic Behavior of Tall Buildings Under Wind: Insights from Full-Scale Monitoring," *The Structural Design of Tall and Special Buildings*, 16, p.471-486, 2007
7. Lagomarsino, S., "Forecast Models for Damping and Vibration Periods of Buildings," *Journal of Wind Engineering and Industrial Aerodynamics*, 48, p.221-239, 1993
8. McNamara, R., Kareem, A. and Kijewski, T., "Ask the Experts...Perception of Motion Criteria for Tall Buildings Subjected to Wind," Proceedings of Structures Congress, ASCE, Denver, 2002
9. Pirnia, J.D., Kijewski-Correa, T., Abdelrazaq, A., Church, J., and Kareem, A., "Full-Scale Validation of Wind-Induced Response of Tall Buildings: Investigation of Amplitude-Dependent Dynamic Properties," Proceedings of the 7th Annual Structures Congress, Long Beach, CA, CD-ROM, 2007
10. Satake, N., Suda, K., Arakawa, T., Sasaki, A., and Tamura, Y., "Damping Evaluation Using Full-Scale Data of Buildings in Japan," *Journal of Structural Engineering*, 129, 4, 470-447, 2003